Increasing Crop Production Benefits to Small Producers in Bangladesh

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ABSTRACT

Agricultural production in South Asia is characterized by intensive use of inputs, such as fertilizers and irrigation water, and by a focus on production of staple crops, especially rice. However, continued growth of the agriculture sector is hampered by a number of challenges. In Bangladesh, these challenges include declining productivity of inputs, resource degradation, and lack of crop diversification. Expansion of agricultural lands is not an option given high population density. Rather, greater efficiency in agricultural production is needed to increase benefits to small producers. This paper examined the benefits of key crop production decisions for rural livelihoods across Bangladesh in order to suggest ways in which producers can increase returns to crop production. The study used plot-level data from a household survey to estimate the relative contribution of various inputs and practices to the total value of production from a given plot over the course of one year. Results were run separately for upper and lower expenditure quintiles to compare production outcomes for richer and poorer households. Three key results emerged: (1) that urea subsidies yielded benefits, though these might not be reaching those that needed it most; (2) that access to groundwater resulted in better production outcomes than access to surface water; and (3) that returns were greater from plots where rice was rotated with other crops.

Keywords: Bangladesh, agriculture, fertilizer, irrigation
JEL Classification: Q1, Q11

INTRODUCTION

Agricultural production remains a major contributor to the livelihood of smallholder producers and the overall economies of South Asia. This is also true for Bangladesh, where agriculture accounts for 16 percent of gross domestic product (GDP) and employs 48 percent of the total labor force (World Bank 2017). Between 2000 and 2010, GDP grew by 6 percent per year and poverty declined by almost two percentage points per year on average. As a result, the share of the population classified as poor fell from 49 percent in 2000 to 32 percent in 2010 and significant achievements were made in terms of nutrition, health, and education outcomes over the same period. However, as of 2010, an estimated 26 million people still live in extreme poverty and are highly vulnerable to livelihood shocks (World Bank 2013). Despite increasing urbanization, 66 percent of the population still resides in rural areas, where the rates of poverty and malnutrition are higher (World Bank 2017).

Given the importance of agriculture to the livelihoods of many poor smallholder producers in rural areas, agricultural growth should be an essential part of any poverty reduction strategy in the country (Irz et al. 2001; Thirtle, Lin, and Piesse 2003; Timmer 2005; Loayza and Raddatz 2009). There is evidence from Bangladesh that growth in agricultural productivity led to declines in rural poverty through increased wages, despite a decline in the amount of hired labor in agriculture (Emran and Shilpi 2017). Increases in agricultural productivity can also contribute to improved food and nutrition security for the growing population, although more evidence is needed to identify the most effective pathways to improve nutrition outcomes through agriculture (Yosef et al. 2015).

In some cases, improvements in agricultural productivity may have direct implications for the nutrition of the poor by making nutrient-rich food, such as fish, more available and affordable (Toufique and Belton 2014).

Despite dramatic improvements in agricultural productivity over the past several decades, serious challenges continue to plague the agriculture sector in Bangladesh. These challenges include scarcity of land due to high population density, declining effectiveness of fertilizers and pesticides, resource degradation due to overapplication of chemicals and intensive year-round cultivation of rice, lack of crop diversification, and climate change. While there is space for the introduction of new technologies (e.g., drought or saline-tolerant crop varieties and further spread of hybrid varieties), given the intensity of crop cultivation at present, greater gains may be made by improving the efficiency of inputs such as fertilizer, diversifying production toward higher value crops, and expanding post-harvest processing and access to markets (Katyal and Reddy 2009; Mujeri et al. 2012; Thomas et al. 2013).

This paper examines the relative benefits in terms of value of production of key cropping decisions and agricultural production practices for rural livelihoods across Bangladesh; using plot-level data from a household survey conducted in late 2011/early 2012. Specifically, an aggregate polynomial regression model that shows the relative contribution of various inputs and practices to the total value of production from a given plot over the course of one production year was estimated. The results from the analysis highlight entry points for policy changes from differences in production outcomes for richer and poorer households.

AGRICULTURAL PRODUCTION IN BANGLADESH IN A REGIONAL PERSPECTIVE

Green Revolution technologies transformed the agricultural system of South Asia through the introduction of high-yielding cereal varieties, the use of chemical fertilizers and pesticides, and the expansion of irrigated areas (Hossain 1988; Sen, Mujeri, and Shahabuddin 2004; Timmer 2005). Crop production in the region has been characterized by intensive use of inputs, such as fertilizers and irrigation, and a focus on production of staple crops, namely, rice and wheat.

Crops are grown over three cropping seasons: the summer monsoon season (kharif-2), the winter season (rabi), and the spring pre-monsoon season (kharif-1). Rice production (aman rice) is widespread during the monsoon season, while a wide range of crops, including boro rice, wheat, maize, winter pulses, potatoes, and mustard are grown in the winter season under irrigation. During the pre-monsoon season, short-duration crops such as maize, pulses, and aus rice are grown (Timsina, Jat, and Majumdar 2010). The selection of crops depends on water availability and soil quality, which vary considerably throughout the region. For example, crops such as mustard, wheat, and cotton have low water requirements and are better able to tolerate salinity while crops like rice, sugarcane, and forages have greater water requirements and are more sensitive to salinity (Sharma and Minhas 2005).

While the introduction of Green Revolution technologies led to dramatic increases in the yields and availability of key staples, agricultural production faces a number of challenges including declining productivity of inputs, resource degradation, land fragmentation, and climate change. Many of these challenges are more pronounced in Bangladesh, where producers focus more heavily on rice cultivation and where the intensity of input use is among the highest in the region (Mujeri et al. 2012; Rahman 2009; Timsina, Jat, and Majumdar 2010).

Throughout the country, agricultural intensification was accompanied by an increase in the area under irrigation and planting of short-duration, high-yielding crop varieties (mostly paddy rice but also wheat). On the other hand, production of many non-rice crops and fisheries declined (Husain, Hossain, and Janaiah 2001; Rahman 2009). More than three quarters of agricultural lands have been dedicated to rice production, and often over several seasons (Ahmed et al. 2013). Monocropping of rice over the entire year and intensive application of inputs, particularly chemical fertilizers and pesticides, have led to a decline in sustainable land management practices, such as mixed cropping, crop rotation, intercropping, and fallowing, and an increase in resource degradation and environmental impacts, such as declining soil fertility and water pollution (Rasul and Thapa 2003; Rasul and Thapa 2004; Rahman 2010). Furthermore, while Bangladesh has a comparative advantage in domestic production of rice at the export parity price, non-rice crops such as vegetables show higher economic returns. This suggests that there are opportunities to diversify production, given investments in processing, marketing, and infrastructure (Sen, Mujeri, and Shahabuddin 2004).

As most food produced is also consumed in the country, cropping decisions also have direct implications for food security and nutrition. While cereals have become more widely available, greater reliance on staple cereals for caloric intake has negative implications for dietary diversity and nutrition (Rahman 2010; Headey and Hoddinott 2015). Furthermore, climate change and extreme climate events, such as flooding, coastal cyclones, regional droughts, and sea level rise, are likely to constrain future agricultural production

(Yu et al. 2010; Ruane et al. 2013). A recent study reveals, however, that the adverse impacts of climate change on agriculture may be reduced through the selection of appropriate cultivars, improved fertilizer efficiency, better pest management, and changes in planting dates for rice, which may have broader implications for crop rotations in general (Thomas et al. 2013).

Given that the country's land resources are already stretched thin due to the demands of a dense and growing population, there is little scope for expansion of cultivated area. Moreover, land fragmentation has been shown to impair agricultural production and technical efficiency (Rahman and Rahman 2009; Rahman and Salim 2013). In addition, the already intensive cultivation of crops leaves little room for the introduction of new technologies, apart from the expansion of hybrid varieties and the introduction of preferred traits, such as drought or saline tolerance. However, there may be potential to improve the effectiveness and efficiency of crop production and to increase the benefits for rural producers through policy changes, changing crop rotations and crop diversification, and expansion of post-harvest processing and access to markets for high-value commodities.

The efficiency of fertilizer use is relatively low in South Asia due to poor quality fertilizers, nutrient mismanagement, absence of complementary inputs, and subsidies targeted at single nutrients (Katyal and Reddy 2009; Mujeri et al. 2012). In Bangladesh, urea is subsidized at a higher rate than other fertilizers (Hossain and Haq 2010). Fertilizer subsidies distort prices and lead to unbalanced and inefficient fertilizer application, such as the overapplication of nitrogen relative to other elements (Mujeri et al. 2012).

In addition to increasing the effectiveness of inputs, crop diversification, and a shift towards more post-harvest value addition and improved marketing of high-value commodities, such as fruits, vegetables, and fish products, may offer households more diversified livelihood sources, better nutrition, and greater income (Hoque 2001; Joshi et al. 2004; Joshi, Gulati, and Cummings 2007; Rahman 2009). Crop diversification is also associated with more sustainable farming practices, such as integrated pest management (Mahmoud and Shively 2004; Rasul and Thapa 2004), and changes in crop rotation may also increase the resilience of agricultural households to confront climate change and extreme events (Thomas et al. 2013).

METHODOLOGY

This study used data from the Bangladesh Integrated Household Survey (BIHS) conducted from October 2011 to March 2012. The survey was implemented by Data Analysis and Technical Assistance Limited (DATA), a Bangladeshi consulting firm with expertise in conducting complex surveys and data analysis, and was supervised by senior researchers at the International Food Policy Research Institute (IFPRI). BIHS was designed to provide data for several studies planned under the United States Agency for International Development (USAID)-funded Bangladesh Policy Research and Strategy Support Program (PRSSP). The following sections on sampling and data mirror descriptions of the same in previous publications based on BIHS data (e.g., Ahmed et al. 2013).

Sample Selection

The BIHS sample is statistically representative at both the national and division levels (i.e., Barisal, Chittagong, Dhaka, Khulna, Rajshahi, Rangpur, and Sylhet). Statistical methods were used to calculate the total BIHS sample size of 6,500 households in 325 primary sampling units (PSUs). BIHS followed a stratified sampling design in two stages—selection of PSUs and selection of households within each PSU—using the sampling frame developed from the community series of the 2001 population census. In the first stage, a total sample of 325 PSUs were allocated among the selected strata with the probability proportional to the number of households in each stratum, which resulted in the following distribution across divisions: 21 PSUs in Barisal, 48 in Chittagong, 87 in Dhaka, 27 in Khulna, 29 in Rajshahi, 27 in Rangpur, and 36 in Sylhet. In the second stage, 20 households were randomly selected from each PSU.

Data

The BIHS questionnaires included several modules that together provided an integrated data platform that answered a variety of research questions and included separate questionnaires for male and female residents in sampled households.

This study relied primarily on data collected using the module on agricultural production and costs, which captured plot-level data on land and soil quality, crops grown, area planted, crop yields, input use and costs, agricultural technologies used, and access to agricultural extension services, among other information. The survey covered the agricultural production year from 1 December 2010 to 30 November 2011. Analysis based on this dataset suffered from two key limitations. The first, common to any cross-sectional analysis, was that there might be unresolved endogeneity issues in the data—i.e., to what extent a positive coefficient for a particular input reflected the benefit of using that input, and to what extent it reflected higher motivation or efficiency on the part of the kind of farmer that tended to use that input. The other, and more significant limitation of these BIHS data was that while crops grown, area planted, and crop yields were reported for all plots, inputs and costs were only recorded for the main plot of the household.

The main plot was defined as the largest plot cultivated by the household, with two exceptions. If two or more plots had the same planted area, then the plot with non-rice cultivation was used as the main plot. Additionally, if the respondent had rented plots in addition to those he or she owned, then separate 'main' plots were selected from both those owned and those rented. The analysis in this paper, therefore, was based on a dataset that consisted almost exclusively of a single main plot per household, with clustering applied at the household level in the cases that multiple main plots per household were collected. Having detailed production data for only one plot of the household prevented the integration of all the production activities of the household, including aquaculture (an important rural source of livelihood in parts of Bangladesh), into a household-level analysis of production.

However, the data allowed an analysis of plot production as a system across three annual seasons. Analysis at the plot level had previously yielded econometric studies on the adoption of soil and water management practices (e.g., Bekele and Drake 2003), as well as on crop-specific input use (e.g., Qaim and Traxler 2005) and the role of specific inputs across certain demographic groups (e.g., Holden and Lunduka 2010). This study approached data most similarly to the last example as the relative roles of different inputs and production practices across poor and wealthy households were examined.

Analytical Methods

All variables in the analysis were constructed directly from the BIHS dataset with the exception of the seasonal rainfall variables, which were created using data from rainfall gauges provided by the Bangladesh Meteorological Department by request and linked to surveyed households using ordinary kriging.[1] The value of production was calculated by multiplying crop yields on each plot by the average market price for that crop as reported in the dataset. All cost and production variables were summed across all crops and all seasons to give one value of production per plot. Labor was reported on a cost basis by multiplying the person-days of both hired and family labor with the average daily wage reported for that labor task in the survey. Table 1 shows the descriptive statistics of the variables used in the analysis. These variables show expected differences between poor and wealthy households (as defined by their level of expenditures). Wealthier households have higher levels of literacy, more years of schooling, and a higher value of assets. They also use higher levels of some agricultural inputs such as pesticides other fertilizers, and labor; however, poorer households spend more on urea and seeds. There are virtually no differences between poor and wealthy households in terms of their sources of water for irrigation.

A polynomial regression model was estimated for the value of production (imputed gross market value of crops produced; in Bangladeshi Taka or BDT/acre[2]) at the plot level accounting for all crops grown on the plot in all seasons, using weighted least-squares regression. Regressions were run separately for the full sample of plots and for plots managed by rich and poor farmers. Relatively poorer and wealthier households were defined by per capita expenditure quintiles. The lower three expenditure quintiles represented the poorest households and the upper two expenditure quintiles represented the richest households.

The analyses were weighted for sample selection at the division level, clustered at the household level in cases where more than one crop or plot was reported by the household, and filtered to remove outliers greater than three standard deviations away from the mean. The form of the regression model is given by:

$$Y_i = \beta_{i,0} + \beta_{i,X}X + \beta_{i,I}I + \beta_{i,F}F + \beta_{i,I^2}I^2 + \beta_{i,IF}IF + \varepsilon_i \qquad (1)$$

where Y_i is the value of production (plot level) per acre for respondent *i; X* is a vector of household and environmental control variables; *I* is a vector of labor, chemical, and other inputs costs; *F* is a vector of dummy variables describing characteristics of the particular crop or plot (including crop type and water source); the vectors I^2 and *IF* represent any quadratic terms or interaction terms of interest (in this case, diminishing marginal returns on fertilizer inputs, and the interaction of irrigation method with fertilizer use); and ε_i is a residual error term implicitly incorporating both random disturbance and any technical inefficiencies. The coefficients β_i in the least squares analysis thus represented the marginal effect of a unit change in the variable of interest.

Descriptive statistics

While the dataset only contained data on inputs and the costs of production for the main plot (and not for all cultivated plots), it contained data on planting and harvesting dates, crops planted, and amount harvested for all plots in the dataset. This section, therefore, presents some descriptive statistics on the full range of plots to show how these compare to the main plots used in the analysis below as well as to show the main crop rotations found in the full sample and the value of harvests associated with these rotations.

1 A method of interpolation for random spatial processes (Ord 1983 in Cressie 1990)

2 1 acre = 0.40 hectare

Table 1. Descriptive statistics of key variables in the study for poor and wealthy households

Variable	Full Sample n = 3,252		Low Expenditure Sub-Sample n = 1,193		High Expenditure Sub-Sample n = 2,059	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Value of production (BDT/acre)	114,600	54,889	112,360	53,714	115,951	55,555
Age of HH head (years)	45.88	13.14	44.27	12.87	46.84	13.21
Literacy of HH head	2.72	1.25	2.45	1.21	2.88	1.24
Education of HH head (years of schooling)	3.35	3.97	2.23	3.22	4.03	4.23
Value of HH assets (BDT)	56	329	21	64	77	413
Extension visit (Y/N)	0.08	0.27	0.05	0.21	0.10	0.29
No. of extension visits	0.23	1.26	0.15	1.30	0.27	1.23
Loan from bank (Y/N)	0.22	0.41	0.18	0.38	0.24	0.43
Loan from lenders (Y/N)	0.11	0.31	0.12	0.33	0.10	0.30
Loan from NGO (Y/N)	0.31	0.46	0.34	0.47	0.28	0.45
Loans from kin (Y/N)	0.26	0.44	0.23	0.42	0.27	0.45
Rainfall (Feb–May 2010)	374	241	371	236	377	244
Rainfall (Jun–Sep 2010)	1,159	412	1,182	405	1,145	416
Rainfall (Oct–Jan 2010)	246	104	240	110	250	100
Rainfall (Feb–May 2011)	369	98	365	94	371	99
Rainfall (Jun–Sep 2011)	1,561	372	1,571	363	1,555	378
Labor (person days)	49,200	47,189	48,972	35,668	49,338	52,945
Pesticide costs (BDT)	2,486	4,122	2,334	3,227	2,578	4,576
Urea costs (BDT)	5,500	3,752	5,545	3,724	5,473	3,769
Other fertilizer costs (BDT)	9,627	10,341	9,584	11,762	9,653	9,384
Tools and animal costs (BDT)	8,869	8,423	8,848	7,823	8,881	8,766
Seed costs (BDT)	10,247	12,959	10,366	13,180	10,175	12,827
Surface water	0.11	0.32	0.11	0.31	0.12	0.32
Groundwater	0.67	0.47	0.68	0.47	0.67	0.47
Surface+Groundwater	0.02	0.14	0.02	0.15	0.02	0.14
Rainfed	0.19	0.39	0.19	0.39	0.19	0.39
use3rice3	0.02	0.15	0.03	0.16	0.02	0.14
use3rice2	0.03	0.18	0.03	0.18	0.03	0.18
use3rice1	0.03	0.16	0.04	0.19	0.02	0.14
use2rice2	0.37	0.48	0.37	0.48	0.37	0.48
use2rice1	0.10	0.30	0.10	0.30	0.10	0.30
use1rice1	0.33	0.47	0.33	0.47	0.33	0.47

Notes: Literacy is a categorical variable for the level of literacy of the household head where *1 = cannot read or write, 2 = can sign, 3 = can read only,* and *4 = can read and write*. Rainfall variables indicate the amount of rain that fell (in mm) during the stated time period. The water variables are dummy variables indicating whether the plot had access to surface water, groundwater, both surface and groundwater, or just rainwater. The *use* variables indicate how many seasons a plot was planted throughout the year and *rice* indicates how many of those seasons were planted with rice. For example, use3rice1 would indicate that the plot was planted in all three seasons but that only one of those seasons was rice planted. The units of other variables are defined in the table. BDT = Bangladeshi Taka.

The data showed that agriculture in Bangladesh is still dominated by rice production with 73 percent of all plots in the sample cultivating rice during at least one cropping season of the year. Comparing cropping choices on just the main plots to the entire sample of plots showed that households' main plots tended to focus more on rice production with only 11 percent of main plots dedicated to the production of non-rice crops compared to 27 percent in the full sample of plots (Table 2).

Figure 1 shows the common crop rotations for all the plots in the sample over the course of the year as well as the value of harvest (in BDT/decimal) of these different crop rotations. This figure again shows the dominance of rice production in Bangladesh. Twenty-six percent of the plots in the sample cultivated boro rice followed by aman rice, while another 18 percent cultivated only boro rice and 11 percent cultivated only aman rice. However, it appeared that intensive rice cultivation over three seasons was not a prevalent crop rotation as it was found on only 1 percent of all plots in the sample. It was also associated with very low revenues. The figure also indicates that plots that cultivated just paddy rice (during kharif I, II, or both) as well as non-rice crops, such as spices and vegetables or fruits (during the rabi season), tended to have higher-value harvests. While Figure 1 does not present net profits from these cropping activities, production returns are further explored in the following analysis.

Table 3 shows the common cropping rotations by division (for cropping rotations found on more than 5 percent of plots in the division). This table again highlights both the importance of rice production across the entire country, as well as the diversity of rice rotations across divisions. Notably, irrigated boro rice was prominent in cropping systems across all divisions except for Barisal, an area flagged under Bangladesh's "Master Plan for Agricultural Development in the Southern Region of Bangladesh" for enhancement of surface water and irrigation potential (for the purpose of expanding boro production) (Bangladesh Ministry of Agriculture and FAO 2013).

RESULTS

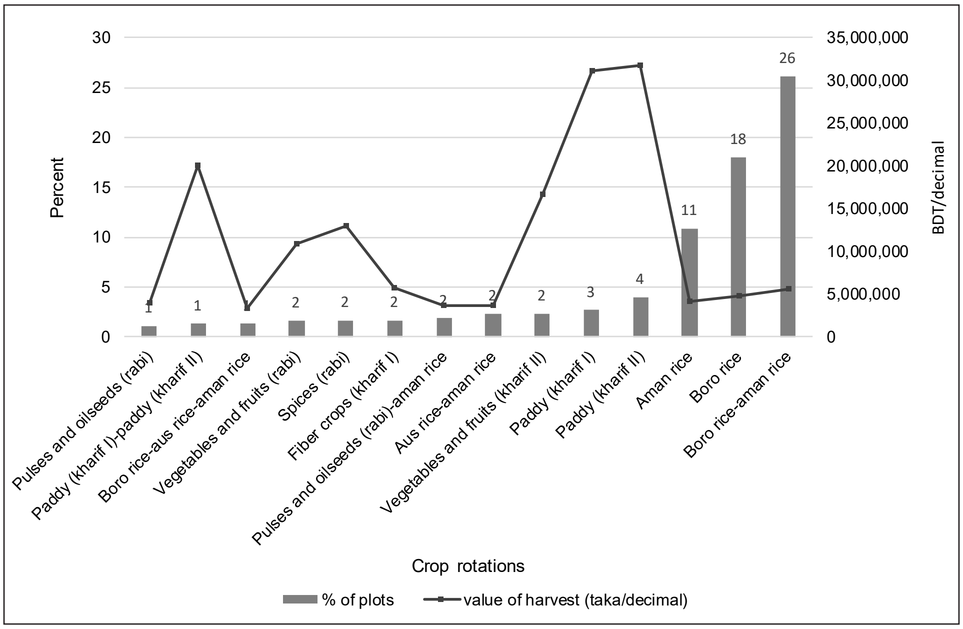
The regression results on the factors influencing value of production are presented in Table 4. The results for each set of explanatory variables—household and environmental controls, inputs, crop and plot characteristics, and quadratic and interaction terms—are discussed below.

Table 2. Prevalence of rice plots in entire sample and sub-sample of main plots

Crop Rotation	All Plots (%)	Main Plots (%)
use3rice3	1.3	2.2
use3rice2	2.0	3.2
use3rice1	2.1	2.3
use2rice2	29.2	35.7
use2rice1	8.9	9.3
use1rice1	29.6	35.8
no rice	27.0	11.4

Note: *Use* indicates how many seasons the plot was planted throughout the year and *rice* indicates how many of those seasons were planted with rice. For example, use3rice1 would indicate that the plot was planted in all three seasons but that only one of those seasons was rice planted.

Figure 1. Common cropping rotations and gross value of harvest



Note: Only cropping rotations planted on more than 1 percent of plots are shown.

Controls

The regressions controlled for household characteristics, including age, literacy, education, household assets, contact with extension services, and outstanding loans. Environmental characteristics were controlled for using district-level dummy variables and seasonal cumulative rainfall (in mm) for the recall period and the preceding season.

Only a few household characteristics explained variation in the value of production of the plot. Greater household assets increased the value of production and this result was significant for richer farm households but not for poorer households. Informal loans from kin were strongly associated with lower values of production across all regressions; and loans from money lenders also had a significant negative impact on value of production for the rich. This reflects limited access to formal credit among rural households. It also suggests that households borrowed from informal sources in order to cope with shocks rather than to make productive investments in agriculture. Contrary to previous studies (e.g., Wadud and White 2000), factors such as age and education had no impact on the value of production.

Environmental controls did not exhibit striking or consistent patterns across the different analyses, with the notable exception of October 2010–January 2011 precipitation, which had a strong negative impact on production over the reporting period (December 2010– November 2011). Overall, the year 2010 had an average monsoon (with 1,434 mm over June–September, compared to a long-term average of 1,491 mm; BARC 2013), but with significant late rains in October and November (303 mm over October–January, compared to a long-term average of 204 mm). The excess rain during this period could have interfered with harvesting and drying aman rice. Above average rainfall was particularly damaging to poorer households (and insignificant for the rich), presumably because these households had less ability to cope with such weather shocks.

Table 3. Common cropping rotations by division (share of plots)

Barisal		Chittagong		Dhaka		Khulna		Rajshanhi		Rangpur		Sylhet	
Common Crop Rotation	**% of Plots**	**Common Crop Rotation**	**% of Plots**	**Common Crop Rotation**	**% of Plots**	**Common Crop Rotation**	**% of Plots**	**Common Crop Rotation**	**% of Plots**	**Common Crop Rotation**	**% of Plots**	**Common Crop Rotation**	**% of Plots**
Aman rice	28.4	Boro rice	25.1	Boro rice-aman rice	30.4	Aman rice	15.6	Boro rice	19.2	Aoro rice-aman rice	45.8	Boro rice	28.0
Aus rice-aman rice	12.7	Boro rice-aman rice	15.7	Boro rice	22.4	Boro rice	12.9	Aman rice	7.9	Aman rice	10.2	Aman rice	19.8
Boro rice-aman rice	11.5	Aman rice	13.6			Boro rice-aman rice	12.6	Paddy seedbed (kharif II)	5.8			Boro rice-aman rice	11.6
Pulses and oilseeds-aman rice	8.6	Vegetables and fruits (rabi)	6.4									Paddy seedbed (kharif II)	10.9
Pulses and oilseeds-aus rice-aman rice	7.1											Aus rice-aman rice	8.0
Paddy seedbed (kharif I)-aman rice	5.8												

Note: Only cropping rotations found on more than 5 percent of plots in the division are shown.

More rainfall between February and May 2011 (early shoulder of the monsoon season) led to increased production for the poor, while reducing the need for irrigation during this period. The results were inconsistent with previous findings that higher rainfall reduced production efficiency of rice farmers in Bangladesh (Mishra et al. 2015).

Controls for the different divisions of Bangladesh suggested reduced agricultural productivity across all divisions relative to the central Dhaka division. However, only a few of these division controls had significant explanatory power over the variability in the dataset—Sylhet and Khulna in the full dataset, Chittagong and Khulna among plots managed by poorer households, and Barisal and Khulna among those managed by wealthier households. The relative production gap across a year for plots in coastal Bangladesh (Khulna, Chittagong, and Barisal) reflected the fact that conditions were not suitable for crop production in this region during parts of the year (especially the rabi season) due to freshwater shortages and soil salinity.

Input Costs

Inputs all showed significant and positive effects on the value of production although the magnitude of the effect tended to be low across all inputs, with the exception of pesticides and fertilizers (especially urea, which was highly subsidized). This suggests an already high level of input intensity across the country, with limited opportunities for further intensification. Earlier studies have found significant potential to improve technical efficiency in agriculture through expansion of irrigation infrastructure, rural electrification, and declines in soil degradation (Wadud and White 2000). The results here suggest that farmers have already achieved a high level of technical efficiency with existing technologies.

Agricultural labor, which was calculated based on the time needed to complete each task (planting, weeding, harvesting, etc.) multiplied by the wage rate, had a return of BDT 0.14[3] for every BDT 1 of effort invested, with the returns to labor higher (0.34) on plots managed by poorer households than those managed by wealthier households (0.13). The low returns to labor effort were likely an indication of surplus labor in agriculture.

Other studies have found higher returns to agricultural labor (Rahman and Rahman 2009). Also, the market wage rate was applied to unpaid family labor, for which the opportunity cost might be lower. Spending on tools, machinery, and animal rental and purchase, also showed low returns of BDT 0.33 across all plots. Returns to tools and machinery on plots managed by richer farmers were higher at BDT 0.46; while the results were insignificant in explaining variation among the poor. Previous studies have found that adoption of high-yielding varieties of seeds increased income of agricultural households in Bangladesh by increasing farmers' productive capacity (Mendola 2007). Results revealed that overall spending on seeds had a significant but low return to production value (BDT 0.34). This finding suggests that investment in higher quality seeds did not necessarily pay for itself, although seed spending by crop type or seed source was not disaggregated in this analysis. This could also point to challenges around seed quality in Bangladesh (Pervez et al. 2017). However, the effect of seed spending was larger for the poor (BDT 0.57) than for the rich (BDT 0.28), which suggests that poorer farmers saw greater incremental benefits to further spending on seeds.

For chemical inputs, the range of application observed across the sample was much broader.

3 The official exchange rate for Bangladeshi Taka (BDT) was BDT 80.41 per USD 1.00 on 1 January 2012.

Table 4. Determinants of value of production

	Full Sample n = 3252 r2 = 0.4861		Low Expenditure Sub-Sample n = 1193 r2 = 0.5262		High Expenditure Sub-Sample n = 2059 r2 = 0.4868	
VOP (BDT/acre/year)	Coeff	SE	Coeff	SE	Coeff	SE
Age of HH head	–22.25	63.81	–110.02	100.44	21.03	83.80
Literacy of HH head	1,203.77	1,193.87	–175.94	1,851.20	2,062.30	1,574.65
Education of HH head	–91.11	373.04	403.04	659.53	–498.97	461.81
Value of HH assets (BDT)	4.23**	1.82	6.94	16.41	3.56**	1.73
Extension visit (Y/N)	210.94	2,558.91	–2,205.95	4,281.73	1,330.91	3,039.46
Loan from bank (Y/N)	2,717.52	1,850.60	–488.05	3,350.46	3,499.14	2,185.67
Loan from lenders (Y/N)	–4,325.93*	2,364.51	–1,893.21	3,472.16	–6,311.54**	3,072.49
Loan from NGO (Y/N)	841.49	1,788.12	–2,201.05	2,581.35	2,761.54	2,403.12
Loan from kin (Y/N)	–9,991.23***	1,752.54	–11,423.68***	2,913.97	–8,984.90***	2,196.17
Rainfall (Feb–May 2010)	6.44	10.96	–15.58	15.52	18.22	14.51
Rainfall (Jun–Sep 2010)	–5.55	8.30	5.34	11.98	–14.34	11.06
Rainfall (Oct–Jan 2010)	–41.12**	16.26	–51.66**	23.80	–31.69	21.17
Rainfall (Feb–May 2011)	–1.50	17.07	55.01**	25.63	–22.32	22.62
Rainfall (Jun–Sep 2011)	1.58	6.15	4.44	9.54	2.17	7.91
Division Barisal	–5,985.76	4,214.33	–3,228.66	6,671.80	–10,401.51*	5,338.41
Division Chittagong	–4,521.98	4,444.15	–22,972.90***	7,597.74	913.01	5,514.87
Division Khulna	–12,048.27***	3,800.77	–13,666.05**	5,717.59	–13,114.59***	4,988.93
Division Rajshahi	–3,648.71	3,256.68	–4,811.42	4,920.98	–2,224.74	4,277.12
Division Rangpur	–938.88	3,994.11	–5,177.62	5,326.12	4,546.30	5,794.81
Division Sylhet	–10,827.40**	4,996.54	–15,111.23*	7,931.45	–8,396.13	6,282.87
Labor (person days)	0.14***	0.04	0.34***	0.10	0.13***	0.05
Pesticide costs (BDT)	0.89**	0.37	1.55*	0.89	1.72***	0.49
Urea costs (BDT)	2.90***	0.69	2.02	1.31	2.72***	0.83
Other fertilizer costs (BDT)	0.96***	0.21	1.11***	0.24	1.01***	0.28
Tools and animal costs (BDT)	0.33***	0.11	0.05	0.16	0.46***	0.13
Seed costs (BDT)	0.34***	0.11	0.57***	0.13	0.28*	0.15
Surface water	12,858.41***	3,744.36	11,047.73**	5,577.40	12,147.44**	4,899.02
Groundwater	21,007.20***	3,315.33	23,587.31***	5,096.21	17,084.98***	4,262.68
Surface + Groundwater	24,106.10***	8,469.10	14,835.57	12,968.87	26,785.68**	10,531.14

Table 4. Continued

	Full Sample n = 3252 r2 = 0.4861		Low Expenditure Sub-Sample n = 1193 r2 = 0.5262		High Expenditure Sub-Sample n = 2059 r2 = 0.4868	
VOP (BDT/acre/ year)	Coeff	SE	Coeff	SE	Coeff	SE
use3rice3	26,846.83***	5,671.60	18,018.90**	8,196.44	31,822.85***	7,701.13
use3rice2	36,788.36***	5,483.27	32,260.21***	8,788.34	41,244.36***	7,081.68
use3rice1	30,047.50***	6,573.11	38,117.47***	8,915.72	24,015.33**	9,491.87
use2rice2	17,329.84***	3,705.59	16,239.88***	6,086.86	17,682.17***	4,550.22
use2rice1	3,007.35	4,203.46	2,042.72	6,761.11	4,246.40	5,192.65
use1rice1	–14,963.77***	3,481.00	–15,038.80**	5,951.95	–13,808.53***	4,153.35
Urea2	–0.03***	0.01	–0.02	0.02	–0.03***	0.01
Other fertilizer2	–4.49E–06*	2.62E–06	–7.69E–06***	2.21E–06	2.90E–05***	7.21E–06
Pesticides2	–1.28E–05**	5.02E–06	–5.96E–05	3.66E–05	–4.73E–05***	7.03E–06
Labor2	–9.41E–08***	3.49E–08	–1.06E–06***	3.66E–07	–8.26E–08**	4.10E–08
Other fertilizer*SW	–0.92	0.75	1.54	1.29	–2.29***	0.85
Other fertilizer*GW	–0.39	0.42	–1.04***	0.37	–1.15**	0.57
Urea*SW	5.04	10.82	10.16	17.96	8.00	12.69
Urea*GW	8.69	9.13	7.56	15.82	18.65	11.31
Constant	73,496.35	9,662.35	50,341.68	14,463.14	79,927.28	12,673.43

Notes: Regressions weighted for sample design, Coeff = coefficient, SE = robust standard errors, and P = p values. Significant at *** 1% (P<0.01), ** 5% (P<0.05), * 10% (P<0.10) levels

Across the full sample of plots, returns to pesticides were BDT 0.89. Rich farmers tended to benefit more from investment in pesticides with returns of BDT 1.72 for each BDT spent, while the poor benefited slightly less from their investment in pesticides (with returns of BDT 1.55). The poor could have benefitted less from spending on pesticides due to poorer farming conditions in general, which reduced returns to pesticides, and lack of information about how to use pesticides effectively (e.g., integrated pest management). In addition, the poor had less money to spend on inputs such as pesticides. Therefore, poor returns to pesticides might also explain why the poor tended to spend less on pesticides than the rich—BDT 2,334 per acre per year compared to BDT 2,578 per acre per year[4] (Table 3).

With regard to fertilizers, the results showed large returns of BDT 2.9 per BDT spent on urea (which was heavily subsidized). These returns were significant only for the rich (BDT 2.72) and not for the poor. The returns to other fertilizers were far less at BDT 0.96 per BDT spent, likely due to their relative lack of subsidy (compared to urea). However, other fertilizers appeared to have slightly higher returns for the poor (BDT 1.11) compared to the rich (BDT 1.01). There was little difference in the level of application of either urea or any other fertilizers between plots managed by rich or poor farmers, although the poor tended to spend slightly more on urea (BDT 5,545

4 Equivalent to BDT 5,835/ha per year and BDT 6,445/ha per year, respectively

compared to BDT 5,473) and the rich tended to spend slightly more on other fertilizers (BDT 9,653 compared to BDT 9,585).

The implication of these results is that spending on urea had a significant role in explaining variation in returns to production across plots managed by wealthier farmers, but not across those managed by poorer farmers. This does not imply that poorer farmers were not benefiting from the subsidy (after all, spending on urea was similarly high on plots managed by both richer and poorer households), but only that variation in spending on urea across plots managed by poorer households did not explain variation in production (see also Mujeri et al. 2012). The implication is that benefits from the urea subsidy (of whatever magnitude) were shared similarly across poorer households, with constraints to other inputs explaining variation in production. This was supported by a more detailed analysis of fertilizer application using the same dataset, which showed that farmers used the recommended amounts of N fertilizer, but underapplied others including triple super phosphate (TSP) and muriate of potash (MoP) (Ahmed et al. 2013).

Another possible explanation could be related to differences in access to fertilizer among different groups of farmers. A number of changes in the fertilizer marketing and distribution system in the country have taken place in recent years and the methods of fertilizer distribution also varied across and within districts (Barkat et al. 2010; Jaim and Akter 2012; Mujeri et al. 2012). For example in some cases, allotment slips, which were not always distributed to farmers fairly, were needed to obtain fertilizer. The distribution system was also plagued with shortages in both the number of dealers and in the supply of fertilizer during critical times of the year leading farmers to purchase fertilizers of variable quality on the open market at higher prices (Barkat et al. 2010; Hossain and Haq 2010). Barkat et al. (2010) further found that fertilizer deficits were more prevalent among farmers with smaller land-holdings, given their limited social power and influence relative to larger landholders. Since fertilizer deficits affected poorer farmers more, they might have been more reliant on fertilizers produced in the open market, which might have been of lesser quality than fertilizers supplied by official distributors.

Water Sources

Given that the dependent variable sums the value of production of the plot over the entire production year (accounting for multiple seasons), plots may draw from more than one source of water across the different seasons. The water source dummy variables accounted for plots irrigated by surface water (which included water from canals, rivers, lakes, ponds, etc., and accounted for 11% of plots) and groundwater (either by deep or shallow tubewells, accounting for 67% of plots) at some point during the production year. A third dummy indicated plots irrigated by both surface and groundwater at different points throughout the year (2% of plots), while the base category accounted for plots that were only rainfed (19% of plots).

The results showed that returns were greatest on plots with access to both surface and groundwater at some point during the production year. However, very few plots in the sample had access to both sources of water throughout the year. Moreover, these results were significant for richer farmers but not for the poor. Plots that relied on groundwater also had significantly higher value of production and the poor appeared to benefit most from access to groundwater. This finding was not surprising given that access to groundwater was especially important for production of profitable rabi crops, such as boro rice, wheat, vegetables, spices, and pulses. Plots that relied on surface water fared better than purely rainfed plots, but worse than those reliant on groundwater or both surface and groundwater. However, plots irrigated with surface water that were managed by rich farmers performed better than those managed by poor farmers.

Another way of interpreting these results is that the difference in production outcomes between plots irrigated by surface and groundwater was less for the rich than for the poor. This could suggest that richer farmers have plots located closer to the surface water offtake, that they have better maintained field canals, and/or are favored in the distribution schedule for surface water. Numerous other studies have pointed to the importance of the expansion of groundwater irrigation, particularly in the northern regions, for the country's rice productivity improvements (and poverty reduction) (Asaduzzaman et al. 2010; Hossain, Naher, and Shahabuddin 2005; Palmer-Jones 2001). However, the sustainability of groundwater irrigation was called into question in some areas due to declining water tables in peri-urban and urban areas and water quality problems, such as increased levels of arsenic (Ahmed et al. 2014; Bell et al. 2015; Chowdhury 2010; Sharma and Minhas 2005; Shamsudduha et al. 2011).

Crop Choices

Previous studies have suggested that there is potential for agricultural diversification to improve production outcomes in the country (Rahman 2009). Therefore, the relative benefit of different crop choices throughout the year was analyzed by including a series of dummy variables to account for the mix of crops planted over the course of one production year (a measure of both production intensity and variety). The data demonstrate a prevalence of crop rotations with one or more rice crops across the year (Figure 1; Tables 2 and 3), and categories developed in Table 2 were used to distinguish crop rotations in the regression analyses. This group included dummy variables for plots that were used for three seasons out of the year, of which rice was planted for one, two, or three of those seasons. It also accounted for plots that were planted in two seasons of which one or two were rice; and for plots that were only planted in one season and grew rice in that season. The base category accounted for all plots not growing rice (but growing other crops in any of one, two, or three seasons). As shown in Table 1, almost three quarters of farmers' main plots were planted with only rice (usually in one or two seasons), while only one quarter was planted with other crops in addition to rice (18%), or no rice at all (11%).

The results showed, unsurprisingly, that plots harvesting three crops per year had higher gross values of production than those planting only two, which in turn had higher values of production than those planting only one. What was surprising was that among those plots planting three crops, the most successful were those that planted two rice crops and one other crop over the course of the year. Plots managed by richer households benefited the most from this rotation. Poorer households obtained a higher value of production from planting only one rice crop out of three crops over the year compared to other rotations. Among households in the lower expenditure group, those who attempted three rice harvests had much lower values of production compared to other rotations involving at least one non-rice crop. However, returns to intensive rice cultivation were much greater for the higher expenditure group compared to the low expenditure group, although still less than when one non-rice crop was included in the rotation. Plots with only one rice crop (and no other crops) performed the worst out of all the production patterns examined and this result was true for both the rich and poor.

Interactions

A number of squared and interaction terms in the analysis were included to look for diminishing returns and substitution effects. Though a number of significant squared terms were observed, the only diminishing return to inputs (indicated by a negative coefficient on the squared term) was for urea, observed for the full sample and for the higher-expenditure subsample, but not significant for the lower-expenditure subsample. This might indicate preferential access to this particular fertilizer subsidy by wealthier farmers.

Given the importance of water management for fertilizer effectiveness (De Datta 1986), several variables were included for the interaction of the source of water (ground and surface) with the type of fertilizer (urea and other fertilizers). While few interaction terms were significant, controlling for these interactions was important to distinguish the direct effects of fertilizer and water inputs. The only significant interaction terms were the interaction of spending on other fertilizers with access to surface water (among the plots in the higher-expenditure subsample) or groundwater (among the plots in both the higher- and lower-expenditure subsamples). These results implied substitution effects—that within the range of variability observed in these subsamples, spending on non-urea fertilizers could compensate for a lack of access to a particular source of water. The relationship between fertilizer and water inputs is likely to be location specific. For example, in the case of Chile, another study found complementarity between fertilizers and irrigation but substitution effects between water and other inputs (Cai, Ringler, and You 2008).

SUMMARY AND IMPLICATIONS

Several key results emerged across these analyses. First, there was limited scope to further intensify input use throughout the country. This was shown by the limited return to inputs such as labor, seed, and machinery, unless new promising technologies are developed and made available. This finding contradicts older studies on technical efficiency of rice production in Bangladesh (Wadud and White 2000), and suggests that farmers have already made considerable efficiency improvements given available technologies.

In terms of fertilizer, the government's investment in the urea subsidy was yielding benefits for farmers, through reduced input costs and increased value of production. However, spending on urea had a significant role in explaining variation in production only across plots managed by wealthier households. Spending on urea was not a significant factor in explaining production for plots managed by poorer households. Per-plot spending on urea was similar across both groups of households, with one possible interpretation being that poorer households were constrained by other inputs. This reflects one of the broader challenges in any development intervention—how to identify what is needed by those in need. It is important to highlight, however, that this analysis only accounted for the cost to the farmer to purchase urea and did not factor in government spending on the subsidy. Therefore, it cannot be stated whether alternative uses of government resources, such as more spending on agricultural research, would be better for agricultural production in the short or long term.

Other analyses suggest that while fertilizer subsidies are popular and provide immediate benefits, urea subsidies contribute to an inefficient allocation of nutrients to the soil, namely, an overapplication of nitrogen relative to other nutrients (phosphorus and potassium), which leads to soil degradation over time (Mujeri et al. 2012). Furthermore, data show that farmers use far less than the recommended doses of TSP and MoP on HYV aman and boro rice (Ahmed et al. 2013).

As soil quality erodes, more fertilizer is needed to maintain yields, a pattern that is unsustainable and has potentially large environmental and human health costs. Therefore, fertilizer subsidies might have also hindered the adoption of more ecological and sustainable agricultural practices that could have greater benefits in the long run. As economies develop, direct input subsidies should be replaced with direct, decoupled farm support or social protection programs targeted to poorer farm households to reduce environmental impacts associated with fertilizer subsidies.

The second key result was that across the sample, access to groundwater provides a greater boost to production than access to surface water. This result is not surprising given that rapid expansion of groundwater extraction was largely responsible for the agricultural development in the country, compounded by the government's relative neglect of the surface water system until recently (Asaduzzaman et al. 2010; Luo and Rahman 2010). Groundwater is used for irrigation of profitable rabi crops, such as boro rice, pulses, vegetables, and spices and is, therefore, associated with higher returns to production. Access to both surface and groundwater by a plot across the year leads to greater benefits. However, this describes only a small fraction of sampled plots, and the effect is not significant for poorer households.

It is worth highlighting that the challenges associated with these different sources are quite different. Surface water quality is generally good, but users have to wait for water to be available (and then, have to wait their turn). Groundwater is typically available on demand, but quality can suffer from the presence of salinity, arsenic, or other dissolved minerals. Both sources could generate significant pumping expenses (low-lift pumps for surface water, tubewell pumps for groundwater) though these costs are likely to be lower for surface water where gravity often takes on much of the burden of delivery. Unfortunately, this study does not have the capacity to account for these costs with the data.

The results demonstrate that the risks of groundwater are low relative to those of surface water, given that farmers can irrigate on demand rather than wait for their turn to access surface water. It remains to be seen in the years to come whether soil salinity or public health responses to arsenic degrade the relative benefits afforded by groundwater use. The results also show that wealthier households appear to have preferential access to surface water, as is the case elsewhere in South Asia, which suggests that there is room for improving the surface water system to make water distribution more equitable through infrastructure improvements and institutional changes.

Third, while high cropping intensities, i.e., planting three crops over the course of the year led to higher productive values of plots overall, planting rice in all three seasons (boro, aman, and aus) was a suboptimal strategy, particularly for the poor. These results support the findings of Rahman (2009) who suggested considerable production gains would result from crop diversification. Shifting rains and changes in flooding patterns could make the coordination of three rice seasons in a single plot prohibitive as indicated by the fact that three rice crops were planted on few plots in the sample. Irrigated (hybrid) boro rice made the largest contribution to productive outcomes at the plot level, followed by high-yielding and hybrid aman varieties. The econometric results suggest that a plot used for boro cultivation should be used for non-rice production during the aman and aus seasons; at most, it could be followed by aman rice. These results also imply that households might benefit from cultivating a more diversified portfolio of crops.

While cultivation of other crops is limited, the data suggest that there is some room to increase production of pulses and oilseeds, spices, vegetables, and fruits during kharif II. These crops could also be cultivated during the rabi season along with other cereals, such as maize and wheat, in the North. Fiber crops also appear to have potential for expansion during the pre-monsoon season (kharif I). However, diversifying crop production would require storage, marketing facilities, and infrastructure to avoid problems of oversupply in local markets. The literature suggests that households with more diverse crop portfolios might also benefit from more sustainable production practices and improved nutrition and livelihood resilience. However, an analysis at the plot level provides an imperfect measure of crop diversification. Rather, there is a need to look across the portfolio of crops grown on all household plots to determine more definitively whether crop diversification leads to greater household income from crop production. This should be an area for future research.

These results have emerged as salient using a large dataset weighted for sample selection at the division level and clustered at the household level to account for any intra-household correlation across plots and seasons. However robust the results may be, the fundamental limitation of this dataset must be emphasized—that it contains data on inputs to production only for the main plot, rather than all plots cultivated by the household. Thus, while the analysis captured inter-seasonal cropping systems within a plot, it failed to capture inter-plot cropping systems within households (such as fallow cycles or integrated aquaculture).

The results highlighted in this study provide useful insights into the ways in which households could adjust their farming practices to receive greater benefits from crop production, as well as the ways in which policymakers could support these changes. In particular, policymakers should consider whether the urea subsidies are having the intended benefits or whether alternative investments would better support smallholder producers and shift agricultural production towards more sustainable practices, including more efficient use of fertilizer.

Similarly, policymakers should be aware that groundwater currently provides greater benefits to farmers than surface water, despite the sometimes poorer quality of groundwater resources. Improvements in the surface water system, particularly related to the timing of water delivery, would need to be made in order to increase benefits to farmers reliant on surface water and potentially shift the burden away from groundwater extraction, the costs of which were not fully incorporated into the analysis. Finally, while households with higher crop rotations on their plots have greater income from agricultural production, for farmers to move beyond traditional crop sequencing and crop choices to cultivate high value crops would require investments in rural infrastructure and institutions that facilitate market access, and rural services, such as credit and extension. Currently, these services are not having the intended effect to improve production outcomes for rural farm households.

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REFERENCES

Ahmed, A.U., K. Ahmad, V. Chou, R. Hernandez, P. Menon, F. Naeem, F. Naher, W. Quabili, E. Sraboni, and B. Yu. 2013. "The Status of Food Security in the Feed the Future Zone and Other Regions of Bangladesh: Results from the 2011–2012 Bangladesh Integrated Household Survey." Report. International Food Policy Research Institute, Dhaka, Bangladesh, 2013.

Asaduzzaman, M., C. Ringler, J. Thurlow, and S. Alam. 2010. "Investing in Crop Agriculture in Bangladesh for Higher Growth and Productivity, and Adaptation to Climate Change." 2010. Report prepared for the Bangladesh Food Security Investment Forum, 26–27 May 2010, Dhaka.

BARC (Bangladesh Agricultural Research Council). 2013. Rainfall (Long-Term Average). Bangladesh: Bangladesh Agricultural Research Council.

Bangladesh Ministry of Agriculture and Food and Agriculture Organization of the United Nations (FAO). 2013. Master Plan for Agricultural Development in the Southern Region of Bangladesh. http://www.fao.org/3/a-au752e.pdf

Barkat, A., R. Faridi, S.N. Waddood, S.K. Sengupta, and S.N.M. Ehsanul Hoque. 2010. "A Quantitative Analysis of Fertilizer Demand and Subsidy Policy in Bangladesh." Final Report PR #9/08. Kushtia, Bangladesh: Manob Sakti Unnayan Kendro.

Bekele, W., and L. Drake. 2003. "Soil and Water Conservation Decision Behavior of Subsistence Farmers in the Eastern Highlands of Ethiopia: A Case Study of the Hunde-Lafto Area." *Ecological Economics* 46 (3): 437–451. doi:10.1016/S0921-8009(03)00166-6

Bell, A.R., E. Bryan, C. Ringler, and A. Ahmed. 2015. "Rice productivity in Bangladesh: What are the benefits of irrigation?" *Land Use Policy* 48: 1–12

Cai, X., C. Ringler, You, J.Y. 2008. "Substitution between water and other agricultural inputs: Implications for water conservation in a River Basin context." *Ecological Economics* 66: 38–50.

Cressie, N. 1990. "The origins of Kriging." Mathematical Geology 22: 239. https://doi.org/10.1007/BF00889887

Chowdhury, N.T. 2010. "Water management in Bangladesh: An analytical review." *Water Policy* 12: 32–51.

De Datta, S.K. 1986. "Improving Nitrogen Fertilizer Efficiency in Lowland Rice in Tropical Asia." In *Nitrogen Economy of Flooded Rice Soils, Developments in Plant and Soil Sciences Vol. 26,* edited by S.K. De Datta and W.H. Patrick, 171–186. Dordrecht, Netherlands: Springer.

Emran, S., and F. Shilpi. 2017. "Agricultural Productivity, Hired Labor, Wages, and Poverty: Evidence from Bangladesh." *World Development.* Published electronically February 22, 2017. doi: 10.1016/j.worlddev.2016.12.009

Headey, D.D., and J.F. Hoddinott. 2015. "Agriculture, Nutrition, and the Green Revolution in Bangladesh." IFPRI Discussion Paper 01423. Washington D.C., USA: International Food Policy Research Institute.

Holden, S., and R. Lunduka. 2010. "Too Poor to Be Efficient? Impacts of the Targeted Fertilizer Subsidy Programme in Malawi on Farm Plot Level Input Use, Crop Choice and Land Productivity." Noragric Report 55. Aas, Norway: Department of International Environment and Development Studies, Norwegian University of Life Sciences (UMB).

Hoque, M.E. 2001. "Crop Diversification in Bangladesh." In *Crop Diversification in the Asia-Pacific Region,* edited by M. K. Papademetriou and F.J. Dent, 5–23. Bangkok, Thailand: Food and Agriculture Organization of the United Nations Regional Office for Asia and the Pacific.

Hossain, M. 1988. “Nature and Impact of the Green Revolution in Bangladesh.” IFPRI Research Report 67. Washington, D.C., USA: International Food Policy Research Institute.

Hossain, M., and F. Haq. 2010. “Fertilizer Marketing and Distribution System: Its Impact on Food Grain Production Household Food Security of the Resource Poor Farmers.” Final Report CF # 4/08. Dhaka, Bangladesh: Center for Agri Research and Sustainable Environment & Entrepreneurship Development.

Hossain, M., F. Naher, and Q. Shahabuddin. 2005. Food Security and Nutrition in Bangladesh: Progress and Determinants. *Journal of Agricultural and Development Economics* 2 (2): 103-132.

Husain, A.M.M., M. Hossain, and A. Janaiah. 2001. “Hybrid Rice Adoption in Bangladesh: A Socioeconomic Assessment of Farmers’ Experiences.” *Research Monograph Series No. 18*. Dhaka, Bangladesh: BRAC Research and Evaluation Division and the International Rice Research Institute Social Science Division.

Irz, X., L. Lin, C. Thirtle, and S. Wiggins. 2001. “Agricultural Productivity Growth and Poverty Alleviation.” *Development Policy Review* 19 (4): 449–466. doi:10.1111/1467-7679.00144

Jaim, W.M.H., and S. Akter. 2012. “Seed, Fertilizer and Innovation in Bangladesh: Industry and Policy Issues for the Future.” Project Paper. Washington, D.C.: International Food Policy and Research Institute.

Joshi, P.K., A. Gulati, P.S. Birthal, and L. Tewari. 2004. “Agriculture Diversification in South Asia: Patterns, Determinants, and Policy Implications.” *Economic and Political Weekly* 39 (24): 2457–2467.

Joshi, P.K., A. Gulati, and R. Cummings (Editors). 2007. *Agricultural Diversification and Smallholders in South Asia*. New Delhi, India: Academic Foundation.

Katyal, J.C., and M.N. Reddy. 2009. “Fertilizer Use in South Asia.” In *Agricultural Sciences Volume 2*, edited by R. Lal, 223–246. Oxford, United Kingdom: EOLSS Publishers Co. Ltd.

Loayza, N.V., and C. Raddatz. 2009. “The Composition of Growth Matters for Poverty Alleviation.” *Journal of Development Economics* 93 (1): 137–151. doi:10.1016/j.jdeveco.2009.03.008

Luo, J., and M.W. Rahman. 2010. "Successful Cases of Irrigation Water Management and Technological Advancement in Bangladesh." Yangling International Agri-Science Forum, 1-3 November 2010, Yangling, China. https://ssrn.com/abstract=1651189

Mahmoud, C., and G. Shively. 2004. “Agricultural Diversification and Integrated Pest Management in Bangladesh.” *Agricultural Economics* 30 (3): 187–194. doi:10.1016/j.agecon.2004.01.001

Mendola, M. 2007. "Agricultural technology adoption and poverty reduction: A propensity-score matching analysis for rural Bangladesh." *Food Policy* 32: 372–393.

Mishra, A.K., K.A. Mottaleb, A.R. Khanal, and S. Mohanty. 2015. "Abiotic stress and its impact on production efficiency: The case of rice farming in Bangladesh." *Agriculture, Ecosystems and Environment* 199: 146–153.

Mujeri, M.K., S. Shanana, T.T. Chowdhury, and K.T. Haider. 2012. “Improving the Effectiveness, Efficiency, and Sustainability of Fertilizer Use in South Asia.” Policy Research Paper 8. New Delhi, India: The Global Development Network.

Palmer-Jones, R. 2001. "Irrigation Service Markets in Bangladesh: Private Provision of Local Public Goods and Community Regulation?" Paper presented at the Workshop on Managing Common Resources at the Department of Sociology, Lund University, Sweden, September 2001.

Pervez, A.K.M.K., Q. Gao, Y. Zeng, and Md.E. Uddin. 2017. "Hybrid Rice: Bangladesh's Failure and China's Success." *Journal of Agriculture and Ecology Research International* 10 (1): 1-10.

Qaim, M., and G. Traxler. 2005. “Roundup Ready Soybeans in Argentina: Farm Level and Aggregate Welfare Effects.” *Agricultural Economics* 32 (1): 73–86. doi:10.1111/j.0169-5150.2005.00006.x

Rahman, S. 2009. “Whether Crop Diversification is a Desired Strategy for Agricultural Growth in Bangladesh?” *Food Policy* 34 (4): 340–349. doi:10.1016/j.foodpol.2009.02.004

———. 2010. “Six Decades of Agricultural Land Use Change in Bangladesh: Effects on Crop Diversity, Productivity, Food Availability and the Environment, 1948-2006.” *Singapore Journal of Tropical Geography* 31 (2): 254–269. doi:10.1111/j.1467-9493.2010.00394.x

Rahman, S., and M. Rahman. 2009. "Impact of Land Fragmentation and Resource Ownership on Productivity and Efficiency: The Case of Rice Producers in Bangladesh." *Land Use Policy* 26 (1): 95–103. doi:10.1016/j.landusepol.2008.01.003

Rahman, S., and R. Salim. 2013. "Six Decades of Total Factor Productivity Change and Sources of Growth in Bangladesh Agriculture (1948-2008)." *Journal of Agricultural Economics* 64 (2): 275–294. doi:10.1111/1477-9552.12009

Rasul, G., and G.B. Thapa. 2003. "Sustainability Analysis of Ecological and Conventional Agricultural Systems in Bangladesh." *World Development* 31 (10): 1721–1741. doi:10.1016/S0305-750X(03)00137-2

———. 2004. "Sustainability of Ecological and Conventional Agricultural Systems in Bangladesh: An Assessment Based on Environmental, Economic and Social Perspectives." *Agricultural Systems* 79 (3): 327–351. doi:10.1016/S0308-521X(03)00090-8

Ruane, A.C., D.C. Major, W.H. Yu, M. Alam, S.G. Hussain, A.S. Khan, A. Hassan, B.M.T.A. Hossain, R. Goldberg, R.M. Horton, and C. Rosenzweig. 2013. "Multi-Factor Impact Analysis of Agricultural Production in Bangladesh with Climate Change." *Global Environmental Change* 23 (1): 338–350. doi:10.1016/j.gloenvcha.2012.09.001

Sen, B., M.K. Mujeri, and Q. Shahabuddin. 2004. *Operationalizing Pro-Poor Growth: Bangladesh as a Case Study.* Washington, D.C., USA: World Bank.

Shamsudduha, M., R.G. Taylor, K.M. Ahmed, and A. Zahid. 2011. "The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh." *Hydrogeology Journal* 19 (4): 901–916.

Sharma, B.R., and P.S. Minhas. 2005. "Strategies for Managing Saline/Alkali Waters for Sustainable Agricultural Production in South Asia." *Agricultural Water Management* 78 (1–2): 136–151. doi:10.1016/j.agwat.2005.04.019

Thirtle, C., L. Lin, and J. Piesse. 2003. "The Impact of Research-Led Agricultural Productivity Growth on Poverty Reduction in Africa, Asia and Latin America." *World Development* 31 (12): 1959–1975. doi:10.1016/j.worlddev.2003.07.001

Thomas, T.S., K. Mainuddin, C. Chiang, A. Rahman, A. Haque, N. Islam, S. Quasem, and Y. Sun. 2013. "Agriculture and Adaptation in Bangladesh: Current and Projected Impacts of Climate Change." IFPRI Discussion Paper 01281. Washington, D.C., USA: International Food Policy Research Institue.

Timmer, P. 2005. "Agriculture and Pro-Poor Growth: An Asian Perspective." Working Paper 63. Washington, D.C.: Center for Global Development.

Timsina, J., M.L. Jat, and K. Majumdar. 2010. "Rice-Maize Systems of South Asia: Current Status, Future Prospects and Research Priorities for Nutrient Management." *Plant and Soil* 335 (1-2): 65–82. doi:10.1007/s11104-010-0418-y

Toufique, K.A., and B. Belton. 2014. Is Aquaculture Pro-Poor? Empirical Evidence of Impacts on Fish Consumption in Bangladesh. *World Development* 64: 609–620.

Wadud, A., and B. White. 2000. "Farm household efficiency in Bangladesh: A comparison of stochastic frontier and DEA methods." *Applied Economics* 32: 1665-1673.

World Bank. 2012. *Bangladesh Economic Update*. Washington, D.C., USA: World Bank.

———. 2013. "Bangladesh Poverty Assessment: Assessing a Decade of Progress in Reducing Poverty, 2000-2010." *Bangladesh Development Series Paper* No. 31. Washington, D.C., USA: World Bank.

———. 2017. *World Development Indicators 2017.* Washington, D.C., USA: The World Bank.

Yosef, S., A.D. Jones, B. Chakraborty, and S. Gillespie. 2015. "Agriculture and Nutrition in Bangladesh: Mapping Evidence to Pathways" *Food and Nutrition Bulletin* 36 (4): 387-404.

Yu, W.H., M. Alam, A. Hassan, A.S. Khan, A.C. Ruane, C. Rosenzweig, D.C. Major, and J. Thurlow. 2010. *Climate Change Risks and Food Security in Bangladesh.* London and Washington, D.C.: Earthscan.